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SEEING BY EXPLORING

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The classical notion of how we see things is that perception is passive—that the eyes are windows, and in floods reality. This was how the Greeks saw perception, and it is the basis of the accounts of the seventeenth and eighteenth century Empiricist philosophers. But physiological work of the nineteenth century cast doubt on this view that perception is passive acceptance of reality. The doubt arose from discoveries of elaborate neural mechanisms, of the delay of signals, and of the time required to process the signals and then make decisions. The doubt was fueled by interest in phenomena of visual and other illusions; for how could passively accepted truth be illusory? It was clear to Hermann von Helmholtz and others and hundred years ago that illusions suggest active processes of perception, which do not always work quite correctly or appropriately. This discovery, and surely this was an important discovery, was not all popular with philosophers—for perception as the principal basis for true statements became suspect. Worse, evidently perception needed scientific backup (and indeed, what was discovered with instruments did not always agree with how things seem to the senses), so philosophers lost out to scientists as the discoverers and arbiters of truth. Fortunately for them, scientists often disagree on their observations, and how they should be interpreted, so philosophy gradually took on other roles, especially advising scientists what to do.

Perhaps curiously, perception is not at the present time a popular topic for philosophers. This must be partly because scientific accounts of perception have now gone a long way away from appearances. They depend on physiological and psycho-physical experiments (as well as curious phenomena including various kinds of illusions) which require technical investigation and do not fall within traditional concepts of philosophy. For example, it has become clear over the last 20 years or so that visual perception works by selecting various features from the environment, by specialized information channels of the eye and brain. This is an extension of the nineteenth century physiological concept of the Specific Energies of nerves, suggested by the founder of modern physiology Johannes Muller (1801-58). His notion that there are many special receptors and neural pathways, each giving its own distinct sensation, has recently been confirmed and extended for touch, hot and cold, and tickle (Iggo, 1982). In vision, various features (such as the position and orientation of edges, direction and velocity of movement, stereoscopic depth, brightness, and colors) are signaled by dedicated channels having special characteristics for transmitting and analyzing significant features of the world. There are also "spatial frequency" channels, tuned to separations of features, which suggest that spectral analysis plays some part in pattern recognition. All this implies that a great deal of parallel processing goes on in the visual system—leading to integrated pattern vision in which many sources of information, sensory and stored from the past, come together—to give powerfully predictive hypotheses, which are our reality of the object world. It seems appropriate and useful to think of perceptions as "hypotheses" (Perceptual Hypotheses) by analogy with the hypotheses of science which make effective use of limited data for control and prediction (Gregory, 1974, 1981).

We may go on to ask further what, perceptually, is an object? What is accepted or seen as an object depends greatly on use—on what is handled, or what behaves, as a unit. It seems that we

map the world into individual objects in infancy, by exploring with our hands and discovering what can be pushed or pulled as units, and generally how things behave to us and to each other. Thus when we read a book, each page is an object, as we turn them separately; but on the shelf each book is an object, as they are selected and picked as a unit. And on a printed page letters, words, sentences, or paragraphs may be units, according to how we read. Perceptual units are set up early in life, but it is an interesting possibility that new structuring might be continued throughout adult life—by continuing to explore the world with our hands and eyes. Then we might continue the remarkable perceptual and intellectual development of childhood throughout life. This is the hope (one might almost say religion) of interactive "hands-on" science centers, including the *Exploratorium* founded by Frank Oppenheimer in San Francisco, and the *Exploratory* we have started in Bristol (Gregory, 1986). They allow people of all ages to discover the world of objects (and something of science and technology, as well as their own perceptions) by active exploration.

The importance of experience through interaction with objects was impressed upon me 25 years ago when my colleague Jean Wallace and I studied the rare case of someone (S. B.) who, after being effectively blind from infancy, received corneal grafts in middle life. This is the situation envisaged by John Locke, following a letter he received from his friend Samuel Molyneux who asked, "Suppose a man born blind, and now adult, and taught by his touch to distinguish between a cube and a sphere of the same metal. . . . Could he distinguish and tell which was the globe, which the cube?" Locke (1690, Bk. II, Chapt. 9, Sect. 8) was of the opinion that "the blind man, at first, would not be able with certainty to say which was the globe, which the cube." And later, George Berkeley (1707) said similarly that we should expect such a man not to know whether anything was "high or low, erect or inverted . . . for the objects to which he had hitherto used to apply the terms up and down, high and low, were such only as affected or were in some perceived by tough; but the proper objects of vision make a new set of ideas, perfectly distinct and different from the former, and which can in no sort make themselves perceived by touch." Berkeley goes on to say that it would take a long time to associate the two. But, contrary to the expectations of the philosophers, we found that directly after the first operation, S. B. could see things immediately that he knew from his earlier touch experience; although for many months, and indeed years, he remained effectively blind for things he had not been able to explore by touch. So Berkeley's assumption that vision and touch are essentially separate is not correct; knowledge based on touch is very important for vision. Most dramatically, S. B. could immediately tell the time by sight from a wall clock on the hospital ward; as he had read time by touch from the hands of his pocket watch, from which the glass had been removed so that he could feel its hands. Even more surprising: following the operation he could immediately read uppercase, though not lowercase letters. It turned out that he had learned uppercase, though not lowercase, letters by touch as a boy at the Blind School from uppercase letters engraved on wooden blocks. The blind children were given only uppercase letters, as lowercase was not used at that time for street signs or brass plates, which it would be useful to read by touching. So the blind school had inadvertently provided the needed controlled experiment, which suggested that active exploration is vitally important for the development of meaningful seeing in children.

Most moving, and most informative, was S. B.'s response to seeing a lathe (which he knew from descriptions) for the first time. Shortly after leaving the hospital, we showed him simple lathe in a closed glass case at the science museum. Though excited by interest, he made nothing of it. Then, with the cooperation of the Museum staff, we opened the case to let S. B. touch the lathe. As reported at the time (Gregory, 1974):

> We led him to the glass case, which was closed, and asked him to tell us what was in it. He was quite unable to say anything about it, except that he thought the nearest part was a handle. (He pointed to the handle of the transverse feed.) He complained that he could not see the cutting edge, or the metal being worked, or anything else about it, and appeared rather agitated. We then asked a Museum Attendant for the case to be opened, and S. B. was allowed to touch the lathe. The result was startling; he ran his hands deftly over the machine, touching first the transverse feed handle and confidently naming it as a "handle," and then on to the saddle, the bed and the head-stock of the lathe. He ran his hands eagerly over the lathe, with his eyes shut. Then he stood back a little and opened his eyes and said: "Now I've felt it, I can see."

S. B.'s effective blindness to objects he did not know as remarkably similar to clinical agnosia, and to Ludwig Wittgenstein's (1953) notion of "Aspect Blindness." In our own experience (or rather lack or it) of ambiguous figures, such as Jastrow's Duck-Rabbit—while it is accepted as a rabbit, the duck features are scarcely seen, disappearing into aspect blindness. This is also dramatic in Rubin's Face-Vases, which disappear in turn, sinking into the ground of the invisibility of aspect blindness, to emerge from nothing as materializing figures. Thus Wittgenstein (1953, p. 213) asks of an imaginary aspect-blind person, presented with the reversing-skeleton Necker Cube figure:

> Ought he to be unable to see the schematic cube as a cube? For him it would not jump from one aspect to another. The aspect-blind will have altogether different relationship to pictures from ours.

We found that S. B. did not experience reversals of these (to us) ambiguous figures. For him they were meaningless patterns of lines, and, in general, pictures were hardly seen as representing objects. From this, I suggest (Gregory, 1981) that perceptual phenomenon of ambiguity should be highly useful for investigating meaning and understanding.

There was evidence that he learned to conceive and perceive space, not only by handling objects but also by walking. In the hospital ward he was able to judge distances of objects such as chairs with remarkable accuracy. But looking down from the window—which was some 40 or more feet high—he described the distance of the ground as about his own body height. He said that if he hung from the windowsill with his fingers, he feet would just touch the ground. Blind people avoid jumping down for they do not know what is (if anything!) below them; they feel carefully with their feet first. So he would have had little or no experience of distances below his feet, except for stairs and occasionally ladders. We may conclude that experience of walking was necessary for seeing distance. This is borne out by our, normal, loss of Size Scaling looking down from a high building, when cars and people and so on look like toys, though for the same horizontal distance they look almost their "correct" sizes.

All this is evidence that perception depends neurally on reading or interpreting sensory signals in terms of experience and knowledge, or by assumptions (which may, however, be wrong and misleading to produce illusions (Gregory, 1968, 1980)) of the object world. The Exploratory aim is to amplify and extend first-hand experience to enrich perception and understanding for children and throughout adult life. The effectiveness of the hands-on approach for teaching has been questioned. But in any case, surely capturing interest is the first essential for more formal methods to be effective. It is hard to believe that learning has to be serious; it is far more likely that play is

vitally important for primates to learn how to exist in the world in which they find themselves. It is fascinating to watch children and adults in this play-experiment situation of individual discovery. Although research is needed to be sure, they certainly give every indication of thinking and learning by doing.

It seems that children do not approach questions or experiments from a vacuum; they generally have performed ideas, which may not be appropriate or coherent, but may be held robustly. They may be discovered (both by their parent or teacher) by setting up predictions. Thus in the Exploratory, experiments with gyroscopes, or the Bernoulli effect, are highly surprising and so reveal erroneous conceptions. Assumptions may of course also be discovered through questioning, and spontaneous questions may reveal how children or adults see, or think they see. According to Jean Piaget and several other authorities, young children hold magical notions of cause, not distinguishing between their own responses and the behavior of inanimate objects, and they tend to hold Aristotelean notions of physics of motion and forces. In 1929, Piaget described children as believing that all objects capable of movement—such as bicycles, and the sun and moon—are alive. And Piaget reported many investigations on perception of conservation (or lack of conservation) of matter, finding that most children before the age of 9, when given various shapes of a lump of clay, do not appreciate conservation of substance. Presumably hands-on experience tends to correct such errors; but how good are adults? A marketing trick is to use odd-shaped bottles to make the contents look larger, which fools most people.

Do children, if implicitly, apply the scientific method to generate their understanding of the world? This was the view of Jean Piaget (1896-1980), the greatest name in the field. Piaget came to favour of an outright empiricism, where logic itself is learned. In *The Child and Reality* (1972), Piaget proposes the following hypothesis (p. 94):

> (a) That at every level (including perception and learning), the acquisition of knowledge supposes the beginning of the subject's (child's) activities in forms which, at various degrees, prepare logical structures; and (b) therefore that the logical structures already are due to the coordination of the actions themselves and hence are outlined the moment the functioning of the elementary instruments are used to form knowledge.

Piaget offers experiments to show effects of inferences during perceptual development in children, showing that perceptions change as inferences change. For example (*The Child and Reality*, p. 95): "A young child is shown briefly two parallel rows of four coins, one being spaced out more than the other: The subject will then have the impression that the longer row has the more coins." Piaget goes on to say that joining the corresponding coins of each row by lines, or joining them in other ways, has different effects for different ages or stages of perceptual development. So Piaget suggests that different inferences about the lines are made, each making the rows of coins appear somewhat different. He also cites an experiment from his laboratory in which the numbers 1 and 7 are shown with their tops hidden, and at different orientations. When the 1 is tilted to the slope of the 7, it is still read as a 1 when ending a sequence likely to be a 1, but otherwise it is seen as a 7. So probability affects perception in children.

Older children's notions are reported in *Children's Ideas in Science*, edited by Rosalind Driver, Edith Guesne, and Andree Tiberghien (1985). This starts with an account by Rosalind Driver of two 11-year-old boys in a practical class measuring the length of a suspended spring, as equal

weights are added to a scale pan. In the middle of the experiment one of the boys unlocked the clamp and moved the top of the spring up the retort stand. He explains:

> This is farther up and gravity is pulling it down harder the farther away. The higher it gets the more effect gravity will have on it because if you just stood over there and someone dropped a pebble on him, it would just sting him, it wouldn't hurt him. But if I dropped it from an airplane it would be accelerating faster and faster and when it hit someone on the head it would kill him.

This reveals the boy's view of gravity, which is not quite ours.

Whether young children ask abstract or philosophical questions has been asked by an American teacher of philosophy, Gareth Matthews in *Philosophy and the Young Child* (1980). As an example, a boy who had often seen airplanes take off, disappearing in the distance, flew for the first time at the age of 4 years. After takeoff, he turned to his father and said in a puzzled voice: "Things don't really get smaller up here."

How do children come to derive reality from appearances? Is a single dramatic experience such as flying for the first time—or discovering that patterns of spectral lines from glowing gases correspond to light from the stars—sufficient for a paradigm change of view or understanding in children? Can adults go back to the drawing board to see the world afresh?

For looking at the details of how perception works, it is convenient to consider somewhat separately the early stages of how patterns and colors are signaled by the retina and analyzed by the initial stages of the brain's perceptual systems, and then the cognitive (knowledge-based) processes of selecting and testing perceptual hypotheses of the objects and situations that we have to deal with to survive. A particular question that concerns us—and we have no clear answer—is how the various signaled features finally come together, without obvious discrepancies. For example, given that color and brightness are signaled by different parallel systems, why don't they lose their registration to separate and produce spurious edges at borders of objects?

Curiously, our mammalian ancestors did not have effective color vision before the primates, including ourselves at the top of the evolutionary tree. So it might be expected that for us brightness contrast is more significant than color contrast for recognizing objects, and this is generally so. The importance of brightness rather than color contrast is clear from the effectiveness of black and white photography. Switching out the color of a TV set does little to impair our perception (apart from watching snooker) except in rather special, though sometimes biologically important, situations. From this simple experiment we can see that color is useful for spotting red berries in green foliage, seeing through camouflage, remotely sensing the edibility of fruit and meat, which could be a major reason why color vision developed in primate evolution. It had already developed, in various forms, in insects, fishes, and birds, but curiously it was lost for mammals, to be reinvested in our immediate primate ancestors.

In some of our experiments, we do the converse of switching out the color of a TV set: we remove brightness differences while preserving color contrast. This gives "isoluminant" displays, which can be seen only by color vision because there are no brightness differences. We have developed several techniques for producing color-without-brightness contrast, usually for a pair of colors, such as red and green. It is important to ensure that they are set to equal brightness for each observer, for there are individual differences of color sensitivities which, when extreme, are

color-blindness (or better, "color anomaly") which is usually reduced sensitivity to (so-called) red or green light. For these experiments it is important that neighboring color regions do not overlap, or have gaps, because such registration errors would produce brightness differences at the color borders. So producing truly isoluminant displays presents some technical problems (and it rarely occurs in nature), but some of the phenomena can be seen in formal color printing when the print has the same brightness as its different-color background. When the print and background have the same brightness, it is difficult to read and the edges of the letters appear "jazzy." The print is unstable, moving around disconcertingly. In spite of the loss of stability, and uncertainty of just where the edges are, there is hardly any loss of visual acuity as measured with a grating test, although letters are more difficult to read. The fact that letter acuity though not grating acuity is impaired suggests that precise *position* of edges (called "phase" information) is lost at isoluminance, though *separations* between nearby features are signaled almost normally. Reading is particularly difficult when letters are closely spaced. They can also lose their individual identities, breaking up into unfamiliar units.

Losses may also be of neurally higher-level brain processes. Most striking is the appearance (or rather, disappearance) of an isoluminant face. This can be shown best with a matrix of red and green dots as in coarse screen printing: when the two colors are set to isoluminance, the face immediately loses all expression and looks flat, with meaningless holes where the eyes and mouth should be. It no longer looks like a face: it becomes meaningless shapes. Although this is a "subjective" observation, it is unmistakable. It is very strong evidence of drastic perceptual loss when only color is available, for almost anything is normally accepted as a face. This, indeed, makes the cartoonist's work possible because just a few lines can evoke an expressive face; so it is remarkable that face perception is so completely lost with isoluminant color contrast. It is important to note that this loss does not occur when a normal brightness-contrast picture is blurred, for example by being projected out of focus, so this loss of face seems to be a central perceptual phenomenon.

The kinds of losses that occur with normal observers at isoluminance are strikingly like the clinical symptoms of amblyopia, or a lazy eye. This "artificial amblyopia" of isoluminance is convenient for experiments because it can be switched on and off and compared with the normal vision in the same individual. Also, we can see what happens and compare our experience with the reports of people who suffer from amblyopia, which is a help for at least intuitive understanding.

A further and dramatic loss is of a certain kind of stereoscopic depth. The American psychologist Bela Julesz discovered, over 20 years ago, that when slightly different random dot patterns are presented, one to each eye, in a stereoscope, regions of dots which are shifted sideways for one eye are seen as lying at a different distance from the rest of the dots which are not displaced. This shows that the brain can compare meaningless dot patterns presented to the eyes and compute depth from small horizontal shifts—which normally occurs for different distances, as the eyes receive slightly different views as they are horizontally separated by a few centimeters. But when the dots are, for example, green on a red background of the same brightness, this stereoscopic depth is lost. We are now comparing this dramatic loss of stereoscopic depth for meaningless dot patterns (which, however, is perhaps never quite complete) with what happens when there are lines and meaningful objects presented in stereoscopic depth to the two eyes. There is some evidence that edges activate different neural mechanisms from the random dots, because a few people have "line" but not "random dot" stereo vision. Perhaps also the meaning, or object-significance, of what is presented may be important in how the brain compares features for perceiving depth.

There is a corresponding phenomenon for movement. When a pair of such random dot figures are alternated, about 10 times/sec, and viewed with one or both eyes, the shifted dot region separates from the rest of the dots and moves right and left. We find that when the dots are set to isoluminance, the displaced dots are lost among the others and no movement is seen (Ramachandran and Gregory, 1978). This is remarkable, because the dots can be quite large, and clearly visible individually, and yet this kind of stereo depth and movement are lost without brightness information.

Visual channels may be isolated in various ways, including selective adaptation to colors (giving colored afterimages); to prolonged viewing of tilted lines (making vertical lines look tilted in the opposite direction); to movement (as in the "movement aftereffect," which was known to Aristotle). We have recently found that continuous *real* movement is signaled by the same neural channel as discontinuous *apparent* (or phi) movement, which may be seen when stationary lights are switched on and off in sequence—provided the gaps in space and time of the apparent movement are not too great (Gregory and Harris, 1984). When the gaps are large (greater than about 10 min arc subtended angle), movement can still be seen, but now it is signaled by a different neural channel, or cortical analyzing system. This we have found by showing that real movement can cancel opposite-direction apparent movement. This is done by illuminating a readily rotating sector disk with stroboscopic short flashes of light set to make it appear to rotate backwards from its true motion, and also with a variable-intensity continuous light. This produces, say, real clockwise movement and, at the same time, apparent anticlockwise movement of the disc. These movements can be set to cancel, or null, but adjusting the relative intensities of the strobe and continuous lights. At the null point there is only a random jitter, with no systematic movement. The null point is not affected by the disturbing effect of adapting to prolonged viewing of movement. The movement aftereffect affects the real and apparent movement equally, which is strong evidence that they are sharing a common channel. The nulling of real against short-range, apparent movement occurs even though the strobe and the continuous lights have different colors, so the eye's three color channels share a common movement system.

There is, however, an interesting limit to the real/apparent-movement shared channel. When the strobe's flash rate is set to give large jumps of the rotating sectors, nulling no longer occurs. The two movements are now seen passing through each other, simultaneously. These observations indicate a shared channel for real- and short-range apparent movement, but a separate channel for long-range movement. It is well known to cartoon film animators that the long-range movement of large jumps between frames has cognitive characteristics, such as being affected by which features are parts of the same object, or are likely to move separately.

An intriguing question is how the various sources of information from different parallel neural channels combine to give unified perceptions of objects. Although neural channels have different characteristics, and in spite of selective adaptations (which affect some channels but not others), and in spite of distortions (which may be dramatic), we do not experience spurious multiple edges. This surely requires some explanation. We suggest that misregistrations are avoided by a process of "border-locking," such that luminance borders pull nearby color edges to meet them (Gregory and Heard, 1979). So spatial registration discrepancies are prevented, although at the cost of some distortions, which may be very evident. Presumably, some visual distortion of size and curvature is not important in nature, although multiple edges, where there should be but one, would be seriously confusing. So, we suggest, registration is maintained by border-locking (where color is slave to luminance) at the cost of some distortion.

It turns out that the classical perspective distortion illusions (such as the Muller-Lyer and the Poggendorf illusions) remain essentially unchanged when presented with their lines having color contrast to their backgrounds, and set to isoluminance (Gregory, 1976). But some illusions, notably the Cafe Wall illusion (Gregory and Heard, 1979), which has no perspective-depth features, appear undistorted when isoluminant. It seems that early sensory processing is affected by isoluminance (as in the parallel lines of the Cafe Wall illusion), but the cognitive reading (or misreading) of perspective depth from converging lines, which can give spatial distortions (Gregory, 1974), is unaffected by isoluminance—it does not matter how the information arrives for cognition.

Recently, David Hubel and Margaret Livingstone (1987) have found strong evidence for separate cortical systems for representing and analyzing luminance and color information. It now seems that color is primarily analyzed by blobs in the third layer of the striate cortex, while orientations, etc., signaled by luminance differences are analyzed by interblob cells at this early stage of visual processing. On a matter of detail, we disagree with one of Hubel and Livingstone's observations, for, as mentioned above, we find that the perspective depth distortion illusions remain at isoluminance; bu they claim that these and all perspective depth disappear. This is not our experience, but no doubt this discrepancy will soon be resolved.

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